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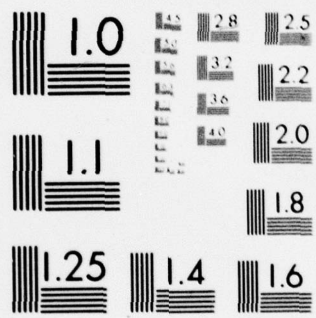

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Cyclic stress-strain response has been studied in copper, variously treated Al-15% Ag alloy, and several variants of 7075 aluminum alloy with different amounts of minor constituents, with the aim of investigating the role of microstructure in such response. Emphasis has been placed on mechanisms of rapid hardening and saturation, on the distribution of slip as controlled by the microstructure and on the relation between the cyclic deformation mechanisms and the fatigue damage mechanisms.

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THE CYCLIC STRESS-STRAIN RESPONSE OF HIGH STRAIN ALUMINUM ALLOYS AND ITS RELATION TO FRACTURE

FINAL REPORT

CAMPBELL LAIRD

MAY 1, 1978

U. S. ARMY RESEARCH OFFICE

DAAG29-75-G-0129

DEPARTMENT OF METALLURGY AND MATERIALS SCIENCE
UNIVERSITY OF PENNSYLVANIA

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INTRODUCTION

In spite of many years of research into fatigue and 100 years of experience in dealing with fatigue problems, fatigue remains a problem of major importance, possessing for vehicles and machinery the nature of cancer for people. Current problems in the DOD involve the notorious C5A wings, helicopters, personnel carrier armor and heavy vehicles. Since cyclic stress-strain response has offered a new line on fatigue, promising to improve design capability[1], and cumulative damage predictions[2], its exploration for aluminum alloys seemed prudent, especially because approaches based on the old S/N philosophy or of linear elastic fracture mechanics do not seem to be providing major advances in understanding the material behavior.

Therefore, the originating proposal for this study called for the completion of previous work on pure metal and binary Al-4% Cu alloy and the following investigations in more complex alloys:

1) Cyclic Stress-Strain Response of Al-15 w/o Ag Alloy

The main purpose here was to check the validity of the "disordering" hypothesis of cyclic softening which had been advanced to explain cyclic response in Al-4% Cu containing θ'' precipitates. Since these precipitates have an ordered structure, it was argued that the repeated cutting motion of dislocations would disorder the strucutre and thus eliminate several sources of hardening[3]. In Al-Ag alloy, the GP zones are disordered in their structure by the process of ageing alone.

Therefore, no further disordering should be produced by cyclic deformation and accordingly no softening is predicted. One goal was to test this prediction.

2) Cyclic Stress Strain Response of Al-Zn-Mg Ternary Alloy and New Commercial Alloys Based on This System

The purpose was to explore the roles of the various hardening agents in these alloys, the dispersoids, constitutent particles and GP zones, in their effect on CSSR. It was also proposed to make a connection between CSSR and the kinetics of crack propagation.

3) CSSR Under Variable Amplitude Loading

The purpose here was to investigate the relationship between CSSR under constant amplitude loading and that under variable amplitude loading. Most design problems involve the latter type of loading and it is necessary therefore to understand general behavior under these conditions. If possible, a connection to life should be made.

4) Coordination With Other Work

Promises were made to keep in close touch with the Frankford Arsenal aluminum alloy group, and with Professors Starke and Fine of Georgia Tech. and Northwestern respectively, who are supported by the Air Force and who are working on related problems. This was accomplished through the regular AFOSR fatigue conferences organised by Dr. Alan Rosenstein and by visits to Frankford/Picatinny Arsenal.

Accomplishments

1) Al-Ag Study

To accomplish the check of the disordering hypothesis,

a batch of alloy was prepared so as to contain GP zones. TEM investigation revealed that the material was indeed treated as desired, except that there was in addition a small sprinkling of the metastable γ' precipitate. CSSR studies have been conducted at length and cyclic hardening was observed to occur at all strain conditions. The "disordering" hypothesis thus appeared supported. Routine TEM investigation of as-cycled alloy yielded a shock, however, in that the cycling definitely produced large quantities of γ'/γ not present at the start of cycling. Much effort was devoted to this problem. This effect has been reported previously by Clark and McEvily but the evidence was not convincing. Unfortunately, their alloy contained large quantities of γ' before cycling so that the claim of increased precipitation was confused with the sampling problem. In light of this difficulty, they also carried out X-ray diffractometry to determine whether γ' transformed to γ but unfortunately chose a line at a low Bragg angle, where peak discrimination was questionable, especially in cycled material and where intensity measurements were invalid because of the large grain size of their specimens. Furthermore, their studies were carried out in long life where more time was available for precipitation.

In the investigation done here, a TEM dark field technique was employed in conjunction with weak beam techniques to discriminate γ/γ' precipitates from dislocations, and the results were unequivocal, as follows. At highest amplitudes (life 100-200 cycles), sizeable γ' precipitates are not present

but diffraction pattern streaking indicated that minute γ' areas were present at regular dislocations, in effect splitting them. Thus the deformation tends both to be planar and reasonably homogeneous. Copious precipitation of γ', of order 0.1μ in diamater, probably converted to γ by dislocation capture (thus relieving coherency stresses), occurred at strains giving lives to failure of the order of a few thousand cycles to failure. This result was most surprising in view of the generally sluggish nature of precipitate growth in the Al-Ag system in the absence of deformation. The kinetics of this growth were studied theoretically and the phenomenon was also explored at lower strain amplitudes. In conclusion, the results at high strain are sufficient to support the "disordering" hypothesis, but clearly, at low strain, the presence of the fatigue-induced metastable and equilibrium precipitates prevents the strain localisation required to produce softening.

We have also completed a related study of CSSR in an Al-Ag alloy containing copious quantities of both dislocations and γ'/γ precipitates. As a result of a mistake(s) by an inexperienced research helper, we initially produced a highly homogeneous precipitated (but γ', not GP zones) Al-Ag alloy which did not show cyclic softening in spite of its high density of dislocations. We later repeated those studies using the same Al-Ag alloy but subject to TMT of a controlled nature. Amusingly enough, we were not able to reproduce the homogeneity achieved by our innocent worker, because the Al-Ag system is plagued by discontinuous precipitation. However, we obtained a reasonably homogeneous structure and the CSSR results

reproduce faithfully except at lower stress levels. We interpret the failure to soften on the basis of the close spacing of the γ'/γ plates, which not only require the material to be hard, but limit dislocation interactions leading to softening. It would be an interesting exercise in phase transformations to detect the processing by which our helper achieved his structure. However, the remainder of the project was granted higher priority.

This work was partly written up in a contribution to the ASTM Symposium "Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth"[4] and more completely in a publication devoted to the alloy containing the GP zone structure[5].

2) <u>CSSR of Al-Zn-Mg Ternary Alloy and Frankford Experimental Alloys</u>

Extensive CSSR studies, including fracture behavior, have been conducted on the following alloys: 1) Frankford 7075-T651, commercial purity, conventionally processed, 2) Frankford high purity 7076-T651 (low in Fe and Si), conventionally processed; 3) Alloy 1, given a final thermo-mechanical treatment, Frankford again; 4) Alloy 2, given a final thermo-mechanical treatment; 5) Pennsylvania Al-Zn-Mg ternary, variously aged; 6) Al-Zn-Mg-Zr alloy, donated by Professor Starke in the T4 and T6 conditions. Both mechanical tests and various types of microscopical observations have been made, and we have also studied behavior in the short and long transverse directions, as well as the processing

direction (only for alloys 1 and 2). TEM observations have been completed on all these alloys. The purpose of studying alloy 6 was to investigate the role of grain size in CSSR. According to Starke, the $ZrAl_3$ particles were supposed to be limited to the grain boundaries and the grain interiors were believed to be hardened by GP zones alone. However, dark field techniques have demonstrated without equivocation that the particles are distributed as a regular dispersoid. We therefore abandoned our grain size study and used this alloy for investigating the role of dispersoid volume fraction. The simplicity of this alloy relative to alloys 1 to 4 has been valuable for interpretive purposes. An overview of this work was presented at the ASTM Symposium mentioned above[4]. The depth of the interpretation has been increased by completing the TEM studies during recent months.

Very briefly, the results are as follows. All of the alloys showed short periods of rapid hardening followed by saturation at high strains, except for the TMT alloys which cyclically softened due to rearrangements of residual dislocations not firmly anchored by precipitation in the final ageing. At low strains, the ternary Al-Zn-Mg alloy aged to contain GP zones did show cyclic softening. Although the structure of these zones is not firmly established, the metastable successor phase η' is ordered, and softening might therefore be expected. Both constituent particles and dispersoids acted to homogenize the slip and to prevent softening, although it was clear that the dispersoids were more effective in doing this than the constituent particles. In

life behavior, the two stage Coffin-Manson plots recognized by Starke were evident, but it was not clear how to explain the behavior. In the final stages of the project, long life tests were still not completed on account of testing competition with respect to other parts of the project. It is anticipated that these tests will soon be completed and publications will be offered during the coming year.

The relationship of CSSR to crack growth was studied in three ways: 1) a straining history typical of that experienced by a ligament of material in the line of advance of a crack was applied to a bulk specimen and the hardening was studied - limited results have been published[4]; 2) mechanisms of crack propagation were studied, especially under variable loading, and a publication resulted[6] and 3) fatigue crack growth kinetics have been gathered using a 'compact tension' type of specimen with the aim of applying the hardening results to these kinetics. The crack propagation model was the plastic blunting process where standard finite element methods were applied to predicting the crack extension per cycle. Here the data are still insufficient to permit publication, but we intend to complete this work.

3) CSSR Under Variable Amplitude Loading

During the CSSR studies described above, all of which were conducted under constant plastic strain, tests were also run under the following variable loading modes: a) block tests, b) incremental tests and c) random tests. It has thus been found that constant strain tests yield equivalent results to those for block tests, but that incremental and random

tests yield cyclic stress-strain curves which are different from that of the constant strain test. The Czech workers, Polak, Klesnil and Lukas have recently offered for publication a paper with the same aim as us but where the investigation was carried out on a wavy slip metal[7]. We have observed many similarities to their results as well as differences, so that understanding of the general problem has now been considerably advanced. Essentially, those materials which show strong resistance to cyclic softening (e.g., our TMT Al-Ag alloy) have incremental or random test CSS curves which lie at higher stress levels than those of the constant test, whereas the relative order is reversed in alloys which show softening due to strain localization and precipitate instability. Generally, however, the differences between the curves are small. Clearly, the curve generated by the incremental test would be most useful for cumulative damage design purposes, because the random test and incremental test yield quite similar curves. The details can be obtained from reference (4). The relationship of these results to questions of alloy design has also been explored[8].

Whilst it would be interesting to study dislocation behavior at different stages during variable loading, most of the alloys studied here are too complex to permit secure interpretation and therefore this aspect of the project can be regarded as complete.

The life aspect of response under variable amplitude loading was studied by Z. Hashin with respect to his new theory of cumulative damage. In this theory[9] damage is defined purely in terms of the number of cycles remaining to failure after a given cycling history. Thus it is mechanism independent. The life predictions produced by it are different from those of Miner's rule and from those of the other approaches to cumulative damage which involve Miner's rule at some point[2]. The theory is however sensitive in some degree to a measure of the endurance limit.

Tests to check the theory have been carried out both with two-stage loading experiments on the Frankford Arsenal 7075 alloys and by tests of data in the literature. The theory is shown to agree extremely well with experiment, and fits Manson's data which he generated to test his double linear damage rule much better than the damage rule. The theory is shown to be a great improvement on Miner's rule.

Tests have also been carried out on block loading spectra, designed to simulate air-ground cycles or step loading sequences. An attempt to check the theory on the Frankford alloys was abandoned when it was found that the acquisition of statistically significant data was beyond the resources of our electrohydraulic testing facility. However, the extensive old work of Lui and Corten who used cheap wire specimens did allow some test of the theory. The theory is thus found to be conservative, and Miner's rule non-conservative. While this result is important, the scatter in the results is discouraging

to Hashin and he is now concentrating on the question of scatter.

4) CSSR in Pure Metals

During the period of the investigation, the field of CSSR in pure metals has been followed closely by the principal investigator. A result obtained by Mughrabi at Stuttgart allowed him to explain the existence of a fatigue limit on a general basis and a paper has been published[10]. Papers have also been published on the history dependence of cyclic response in pure metals[11], the effect of dislocation substructures on fatigue[12], and on other topics[13-15]. Also two invited reviews have been published[16, 17].

As a result of discussions prompted by the conference at which reference 16 was presented, a fruitful collaboration with Doris Kuhlmann-Wilsdorf was initiated on dislocation behavior in fatigue. Initially, the main concern was the formation of persistent slip bands and the subsequent behavior of dislocations within them. Essentially, we believe that the PSB strain is carried by screw dislocations cooperatively in the channels between the dislocation hedges in the PSB's. The model is consistent with the observations so far gathered and also explains the behavior of extrusions[18].

Since that time we have been concentrating on another theoretical study of dislocation behavior in fatigue, but that which occurs during rapid hardening. In December 1977, we completed a paper on this subject (reported in interim report No. 7), but one of the authors (A. Winter) disagreed

about the distribution of strain in dislocation veins. The paper was accordingly withdrawn and so greatly enlarged in subsequent discussion that we have entirely revised and expanded the work, which is now to be presented in three parts. The first part evaluates fatigue hysteresis loops to obtain data for the friction stress and back stress acting on the dislocations. Part of the friction stress is equal in magnitude to the back stress and, like it, rises in proportion to the root of the cumulative plastic strain. The smaller part of the friction stress depends more or less linearly on the number of cycles. It is identified, primarily, with the stress required for dragging the jogs on the screw dislocations which shuttle in the channels defined by veins. Following up on a corresponding hypothesis previously advanced[18], we suggest that the channel widths in the matrix structure adjust such that, on the average, one jog resides on each screw dislocation segment. Accordingly the channel width should decrease inversely with the number of cycles during the early part of the fatigue life. This part of the study has now been completed[19]. In subsequent parts, we are ready to present a theoretical treatment of that component of the friction stress which is coupled to the back stress as well as the back stress itslef and the associated dislocation mechanisms.

SUMMARY

In summary, a range of studies dealing with the cyclic stress-strain response of pure metal, simple precipitation hardened alloy, and complex aluminum alloys has been completed. Emphasis has been placed on the mechanisms of

rapid hardening and saturation in these materials, on the distribution of slip as controlled by the microstructure and on the relation between the cyclic deformation mechanisms and the fatigue damage mechanisms.

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